Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
12 (2008) 235–249

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

Modeling of hybrid renewable energy systems

M.K. Deshmukh[a], S.S. Deshmukh[b,*]

[a]Birla Institute of Technology and Science, Pilani—Goa Campus, Zuari Nagar, Goa 403 726, India
[b]Centre for Renewable Energy and Environment Development (CREED), Mechanical Engineering Group, Birla Institute of Technology and Science (BITS), Pilani Campus, Pilani 333 031, India

Received 15 June 2006; accepted 31 July 2006

Abstract

Hybrid renewable energy systems (HRES) are becoming popular for remote area power generation applications due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. Economic aspects of these technologies are sufficiently promising to include them in developing power generation capacity for developing countries. Research and development efforts in solar, wind, and other renewable energy technologies are required to continue for, improving their performance, establishing techniques for accurately predicting their output and reliably integrating them with other conventional generating sources. The paper describes methodologies to model HRES components, HRES designs and their evaluation. The trends in HRES design show that the hybrid PV/wind energy systems are becoming gaining popular. The issues related to penetration of these energy systems in the present distribution network are highlighted.

Keywords: Hybrid renewable energy systems; Modeling; Optimization; Penetration potential

Contents

*Corresponding author. Tel.: +91 1596 243473; fax: +91 1596 244183.
E-mail address: ssd@bits-pilani.ac.in (S.S. Deshmukh).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2006.07.011

1. Introduction

Solar and wind energy are non-depletable, site-dependent, non-polluting, and potential sources of alternative energy. Utilization of solar and wind power has become increasingly significant, attractive and cost-effective, since the oil crises of early 1970s [1]. However, common drawback with solar and wind energy is their unpredictable nature. Standalone photovoltaics (PV) or wind energy system, do not produce usable energy for considerable portion of time during the year. This is mainly due to dependence on sunshine hours, which are variable, in the former case and on relatively high cut-in wind speeds, which range from 3.5 to 4.5 m/s, in the latter case resulting in under utilization of capacity [2]. In general, the variations of solar and wind energy do not match with the time distribution of demand. The independent use of both the systems results in considerable over-sizing for system reliability, which in turn makes the design costly [1]. The initial cost of solar or wind energy system is higher than diesel engine generator of comparable size but the operating and maintenance costs are always lower than that for the diesel engine generator. As the advantages of solar and wind energy systems became widely known, system designers have started looking for their integration. The term hybrid renewable energy system (HRES) is used to describe any energy system with more than one type of generator usually a conventional generator powered by diesel, and a renewable energy source such as PV, wind, and PV/wind. For remote areas, HRES are often the most cost-effective and reliable way to produce power. However, solar and wind energy into a HRES can attenuate fluctuations in power produced, thereby significantly reducing energy storage requirements [1,3].

Over the last decade, HRES have become viable alternatives for power production because they allow designer to capitalize on the strengths of both conventional and renewable energy sources. The HRES invariably includes battery storage to meet the demand when either the demand is peak load demand or renewable energy source is not available. Battery storage also smoothen the mismatch between time of occurrence of peak load and maximum power generated.

The HRES design is mainly dependent on the performance of an individual system. In order to predict performance, individual components should be modeled first and then their mix can be evaluated to meet the demand reliably. If the power output prediction

from these individual components is accurate enough then the resultant combination will deliver power at the least cost. This approach is adopted by researchers. The present paper aims at reviewing the current state of HRES modeling with particular reference to solar and wind energy. Methodologies generally adopted for modeling system component are described. This is followed by review of work reported by several authors. The paper also discusses need of future consideration in the design of HRES.

2. Modeling of hybrid renewable energy system components

Various modeling techniques are developed by researchers to model components of HRES. Performance of individual component is either modeled by deterministic or probabilistic approaches [4]. General methodology for modeling HRES components like PV, wind, diesel generator, and battery is described below:

2.1. Modeling of photovoltaic system

The input energy to PV system is solar radiation and total solar radiation on an inclined surface is estimated as

$$I_{\mathrm{T}} = I_{\mathrm{b}}R_{\mathrm{b}} + I_{\mathrm{d}}R_{\mathrm{d}} + (I_{\mathrm{b}} + I_{\mathrm{d}})R_{\mathrm{r}}, \tag{1}$$

where I_{b} and I_{d} are direct normal and diffuse solar radiations, R_{d} and R_{r} are the tilt factors for the diffuse and reflected part of the solar radiations [5].

The total solar radiation thus estimated depends on position of sun in the sky, which varies from month to month. Hourly power output from PV system with an area A_{pv} (m^2) on an average day of jth month, when total solar radiation of I_{T} ($\mathrm{kW\,h/m^2}$) is incident on PV surface, is given by [6]

$$P_{\mathrm{s}j} = I_{\mathrm{T}j}\eta A_{\mathrm{PV}}, \tag{2}$$

where system efficiency η is given by [7]

$$\eta = \eta_{\mathrm{m}}\eta_{\mathrm{pc}}P_{\mathrm{f}} \tag{3}$$

and, the module efficiency η_{m} is given by

$$\eta_{\mathrm{m}} = \eta_{\mathrm{r}}[1 - \beta(T_{\mathrm{c}} - T_{\mathrm{r}})], \tag{4}$$

where η_{r} is the module reference efficiency, η_{pc} is the power conditioning efficiency, P_{f} is the packing factor, β is the array efficiency temperature coefficient, T_{r} is the reference temperature for the cell efficiency and T_{c} is the monthly average cell temperature [8] and can be calculated as follows:

$$T_{\mathrm{c}} = T_{\mathrm{a}} + \frac{\alpha\tau}{U_L}I_{\mathrm{T}}, \tag{5}$$

where T_{a} is the instantaneous ambient temperature, $U_L/\alpha\tau = I_{\mathrm{T,NOCT}}/(\mathrm{NOCT} - T_{\mathrm{a,NOCT}})$, and NOCT is normal operating cell temperature, $T_{\mathrm{a,NOCT}} = 20\,^{\circ}\mathrm{C}$ and $I_{\mathrm{T,NOCT}} = 800\,\mathrm{W/m^2}$, for a wind speed of $1\,\mathrm{m/s}$.

2.2. Modeling of wind energy system

Power output of wind turbine generator at a specific site depends on wind speed at hub height and speed characteristics of the turbine. Wind speed at hub height can be calculated by using power-law equation [9]:

$$V_z = V_i \left[\frac{Z}{Z_i}\right]^x, \tag{6}$$

where V_z and V_i are the wind speed at hub and reference height Z and Z_i, and x is power-law exponent.

Fig. 1 shows typical wind turbine characteristics. Power output P_w (kW/m^2) from wind turbine generator can be calculated as follows [10]:

$$\begin{aligned} &P_w = 0, && V < V_{ci}, \\ &P_w = aV^3 - bP_r, && V_{ci} < V < V_r, \\ &P_w = P_r, && V_r < V < V_{co}, \\ &P_w = 0, && V > V_{co}, \end{aligned} \tag{7}$$

where $a = P_r/(V_r^3 - V_{ci}^3)$, $b = V_{ci}^3/(V_r^3 - V_{ci}^3)$, P_r is the rated power, V_{ci}, V_{co} and V_r are the cut-in, cut-out and rated speed of the wind turbine.

Actual power available from wind turbine is given by [10]

$$P = P_w A_w \eta, \tag{8}$$

where A_w is the total swept area, η is efficiency of wind turbine generator and corresponding converters.

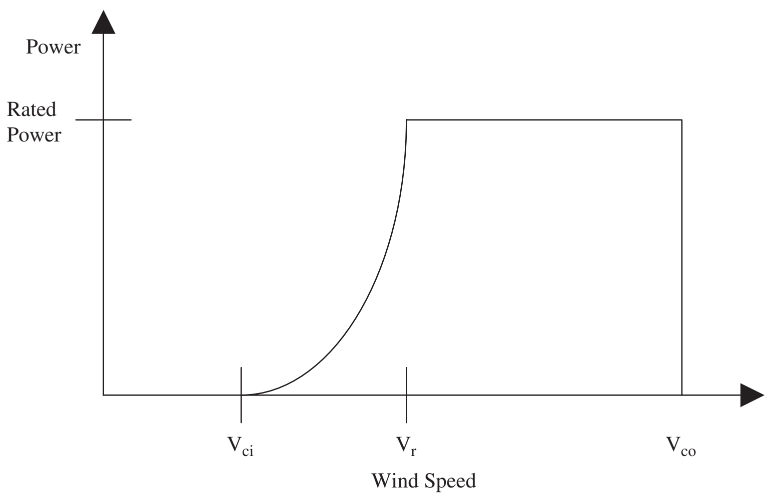

Fig. 1. Wind turbine characteristics.

2.3. Modeling of diesel generator

If the load requirements are not met by either renewable energy system or by batteries (due to state of charge) then load requirements are met by operating diesel generator in HRES. The choice of diesel generator depends on type and nature of the load. To determine rated capacity of the engine generator to be installed, following two cases should be considered [3]:

1. If the diesel generator is directly connected to load, then the rated capacity of the generator must be at least equal to the maximum load, and
2. If the diesel generator is used as a battery charger, then the current produced by the generator should not be greater than $C_{Ah}/5\,A$, where C_{Ah} is the ampere hour capacity of the battery.

Overall efficiency of diesel generator is given by [11]

$$\eta_{overall} = \eta_{brake\ thermal} \times \eta_{generator}, \tag{9}$$

where $\eta_{brake\ thermal}$ is brake thermal efficiency of diesel engine. Normally, diesel generators are modeled in the control of the hybrid power system in order to achieve required autonomy. It is observed that if the generator is operated at 70–90% of full load then it is economical [12]. In the absence of peak demand, diesel generators are normally used for meeting load requirements and for battery charging.

2.4. Modeling of battery system

Battery storage is sized to meet the load demand during non-availability period of renewable energy source, commonly referred to as days of autonomy. Normally days of autonomy is taken to be 2 or 3 days. Battery sizing depends on factors such as maximum depth of discharge, temperature correction, rated battery capacity and battery life. Required battery capacity in ampere hour is given by [13]

$$B_{rc} = \frac{E_{c(Ah)} D_s}{(DOD)_{max} \eta_t}, \tag{10}$$

where $E_{c(Ah)}$ is the load in ampere hour, D_s is the battery autonomy or storage days, DOD_{max} is the maximum battery depth of discharge, η_t is the temperature correction factor.

Difference between power generated and load, decides whether battery is in charging or discharging state. The charge quantity of battery bank at the time t can be calculated by [14]

$$E_B(t) = E_B(t-1)(1-\sigma) + \left(E_{GA}(t) - E_L(t)/\eta_{inv}\right)\eta_{battery}, \tag{11}$$

where $E_B(t)$ and $E_B(t-1)$ are the charge quantities of battery bank at the time t and $t-1$, σ is the hourly self-discharge rate, $E_{GA}(t)$ is the total energy generated by renewable energy source after energy loss in controller, $E_L(t)$ is load demand at the time t, η_{inv} and $\eta_{battery}$ are the efficiency of inverter and charge efficiency of battery bank.

Charge quantity of battery bank is subject to the following constraints:

$$E_{B_{min}} \leqslant E_B(t) \leqslant E_{B_{max}}, \tag{12}$$

where $E_{B_{max}}$ and $E_{B_{min}}$ are the maximum and minimum charge quantity of battery bank.

3. Criteria for hybrid renewable energy systems selection

Various researchers have evaluated HRES using different methods such as energy to load ratio, battery to load ratio, and non-availability of energy. In order to select an optimal combination of a HRES to meet the demand, evaluation may be carried on the basis of reliability and economics of power supply. Reliability of the system is expressed in terms of LOLP or autonomy and net present value. The commonly used methodologies for evaluation of HRES as follows:

3.1. Loss of load probability

The LOLP is given by the following [58]:

$$\mathrm{LOLP} = \frac{\sum_{i=1}^{n} \mathrm{hours}\left(I_{\mathrm{supply}}(t) < I_{\mathrm{needed}}(t)\right)}{n}, \tag{13}$$

where

$$I_{\mathrm{needed}}(t) = \frac{L(t) - P_{\mathrm{W}}(t) - P_{\mathrm{PV}}(t)}{V_{Ll}} \eta\left(I_{\mathrm{battery}}(t)\right), \tag{14}$$

$$I_{\mathrm{supply}}(t) = \min\left(I_{\max} = \frac{0.2\mathrm{SOC}}{\Delta t}, \frac{\mathrm{SOC}(t)\sigma - \mathrm{SOC}_{\min}}{\Delta t}\right), \tag{15}$$

and $I_{\mathrm{needed}}(t)$ is the current required for the load at hour t, $I_{\mathrm{supply}}(t)$ is the current supplied by HRES at hour t, n is number of samples. V_L is the nominal voltage needed by the system, $L(t)$ is the electrical load requirements at hour t, $P_{\mathrm{W}}(t)$ is the power generated by the wind turbine at hour t, $P_{\mathrm{PV}}(t)$ is the power generated by PV modules at hour t.

It is observed that this type of analysis helps system designer to find out LOLP for HRES. If LOLP is low then it results in high cost of the system and vice versa.

3.2. Cost analysis

Life cycle cost (LCC), have been used to decide economic feasibility of the system. The system with lowest LCC is always preferred. LCC is either calculated with or without accounting depreciation of the system by following [17]:

$$\mathrm{PV} = \sum_{k=1}^{t} \frac{C_t}{(1+i)^t}, \tag{16}$$

$$\mathrm{PV_D} = (C+m)_{\mathrm{pv}} + (C+m)_{\mathrm{wind}} + (C+m)_{\mathrm{battery}} + (C+m)_{\mathrm{diesel}} - D, \tag{17}$$

where PV and $\mathrm{PV_D}$ are the present value of the system without and with depreciation, t is the time of analysis, i is the interest rate per year, C_t is the cost in year t, m is the maintenance cost of the system, and D is the present value of depreciation.

Several researchers have extensively used cost of electricity generated as a deciding term to evaluate HRES configuration, at the predefined LOLP. The cost per kWh has been

found useful for the evaluation of HRES. Cost of Electricity per kW h is given by

$$\text{cost}, \$/\text{kWh} = \frac{C_{\text{actual}}}{\text{electricity}}, \tag{18}$$

where C_{actual} is the annualized cost, and electricity is the annual average generation.

4. Review of hybrid renewable energy system modeling

Several HRES configurations such as PV–battery, PV–diesel, wind–battery, wind–diesel, PV–wind–battery, and PV–wind–diesel–battery are shown to be commercially viable. Current status of HRES modeling utilizing solar and wind energy is discussed as follows:

4.1. Hybrid photovoltaic system

Hybrid PV systems are best suited to reduce dependence on fossil fuel by using available solar radiations. Hybrid PV system includes PV generator, diesel generator and/or battery system. Battery storage increases the flexibility of system control and adds to overall system availability. These energy systems have good prospects and many opportunities in hot climates [15,16]. These energy systems are termed as one of the cost effective solutions to meet energy requirements of remote areas. Economic viability of hybrid PV system for decentralized power generation carried out and proved its usefulness for small villages with up to 100 families [17].

Various models including probabilistic or deterministic approaches have been developed to assess the performance of hybrid PV system and to find optimal mix of PV with diesel. The energy system modeled includes both, the system with battery storage and system without battery storage. Modeling battery storage system with respect to the state of charge, optimal size of hybrid PV system can also be obtained [18]. El-Hefnawi [12] used a mathematical technique to calculate minimum number of storage days and minimum PV array area for hybrid PV system. Shrestha and Goel [19] demonstrated a method to find optimal combination of PV array size and battery to meet the refrigeration load, by using statistical models for both solar radiation and the load.

PV battery hybrid system can also be modeled by an iterative optimization technique [20]. In iterative optimization technique, optimal mix can be decided on the basis of cost of electricity generated. Cost of electricity generation can also be justified on the basis of extension from the nearest power line. The tilt and azimuth angle for optimum performance of PV system are dependent on the geographical location, i.e. latitude, longitude and season. Bhuiyan and Asgar [13] optimized PV battery system for Dhaka, Bangladesh with respect to power output for different tilt and azimuth angle for optimum performance of hybrid PV system.

Performance of hybrid PV system is evaluated on the basis of reliability of power supply under widely varying conditions. Reliability is expressed in terms of loss of power supply probability (LOLP) [21]. Egido and Lorenzo [22] reviewed methods for computing capacity of PV arrays and battery storage and suggested analytical model based on LOLP. Notton et al. [3] presented mathematical model for sizing hybrid PV system on the basis of LOLP. The authors have highlighted that optimal solution can be obtained if PV contributes for 75% of the energy requirements. Cost of electricity generated from hybrid PV system is also one of the decision-making parameters. Marwali et al. [23] developed a

methodology for calculating production cost of hybrid PV battery system in which the size of PV system is calculated on the basis of electrical requirements not met.

Wichert [24] reviewed practices of PV–diesel system operation. Author has highlighted need for maintenance free energy storage system, fully automatic energy management system, and reliability of power conditioning devices to increase the competitiveness of these systems.

4.2. Hybrid wind energy system

In order to use hybrid wind energy system effectively and economically, chosen site should have good potential of wind energy [25]. Moreover, technical feasibility and economic viability studies are to be carried out, in addition to capacity meeting of the demands [26–30]. In order to predict the performance of wind turbine generator, forecasting models based on regression analysis, Monte-Carlo simulation technique, and neural network were reported by the researches [31–33]. Capacity factor of wind turbine is also one of the deciding parameters to choose a particular type of wind turbine at the selected site, as an essential component of hybrid wind system [34]. Optimal site planning for wind turbine installation also plays an important role in wind power production [35,36]. Hybrid wind energy system control studies are also been reported in literature [37–39].

Celik [40] developed simplified method for estimating the monthly system performance of wind energy systems. The method requires Weibull wind speed distribution parameters on a monthly basis, the energy to load ratio and battery to load ratio and some model parameters as input. The model results in monthly autonomy of the system. The approach has been found useful for estimating the performance of the system in absence of hourly wind data.

Battery backup in hybrid wind energy system increases its availability. Elhadidy and Shaahid [1] calculated optimum battery storage size for hybrid wind energy system by studying an impact of variation of battery storage capacity on hybrid power generation. Trade off between size of the storage capacity and diesel power required for the load assuming a constant wind power output was reported by the authors. Hybrid wind systems are also evaluated on the basis of LOLP [42]. For a given LOLP, optimal mix of wind, battery and diesel power can be obtained. Penetration potential of wind energy system on a network basis are also reported [43,44].

4.3. Hybrid photovoltaic/wind energy system

Standalone commercial PV or wind, do not produce usable energy for considerable portion of time during the year. Combination of PV and wind in a hybrid energy system reduces the battery bank and diesel requirements. Feasibility of hybrid PV/wind energy system strongly depends on solar radiation and wind energy potential available at the site. Various feasibility and performance studies are reported to evaluate option of hybrid PV/wind energy systems [2,45–48]. PVs array area, number of wind machines, and battery storage capacity play an important role in operation of hybrid PV/wind-diesel system while satisfying load [1]. Nehrir et al. [63] presented computer-modeling approach for evaluating the general performance of hybrid PV/wind energy system. Celik [62] proposed a technique to evaluate performance of hybrid PV/wind energy system using synthetically generated

weather data. Kolhe et al. [8] elaborately discussed the analytical model for predicting the performance of hybrid PV/wind energy system with hydrogen energy storage for long-term utilization.

Optimum size of hybrid PV/wind energy system can be calculated on an hourly basis [14] or on the basis of daily average power per month, the day of minimum PV power per month, and the day of minimum wind power per month [49]. Ai et al. [14] presented method for optimum size of hybrid PV/wind energy system. Performance of hybrid PV/wind energy system was compared on hourly basis; by fixing the capacity of wind generators, yearly LOLP with different capacity of PV array and battery bank were calculated. Trade off curve between battery bank and PV array capacity for given LOLP helps to find optimum configuration at least cost.

Various optimization techniques such as linear programming [20,51], probabilistic approach [4,52], iterative technique [20] dynamic programming [53], multi-objective [54] were used by researchers to design hybrid PV/wind energy system in a most cost effective way. In order to calculate reliability/cost implications of hybrid PV/wind energy system in small isolated power systems Karki and Billinton [44] presented a Monte-Carlo simulation approach. Samarakou et al. [56] compared results of two optimization techniques based on simplex and other algorithm for hybrid PV/wind energy system.

Al-Ashwal and Moghram [57] presented a method for assessment on the basis of LOLP to decide an optimal proportion of PV and wind generator capacities in hybrid PV/wind energy system; optimal system combination was selected on the basis of capital cost and annual autonomy level. Autonomy level of the system is defined in terms of LOLP and is been used to find system configuration [58,59]. Protogeropoulos et al. [60] developed general methodology by considering design factor such as autonomy, for sizing and optimization. The authors also calculated battery size requirements to achieve desired level of autonomy by using system performance simulation model. It is observed that for achieving high autonomy, a backup generator is required and in turn reduces battery storage capacity. Hennet and Samarakou [61] discussed approach to optimize hybrid PV/wind/battery system with conventional power plant and calculated optimal system configuration on the basis of LCC.

The monthly combinations of solar and wind resources lead to solar biased month, wind biased month and months with even solar and wind resource. Total system cost and the unit cost electricity generated for a lifetime of system may be analyzed with respect to the yearly system performance. Celik [62] presented techno-economic analysis based on solar and wind biased months for autonomous hybrid PV/wind energy system. Author has observed that an optimum combination of the hybrid PV/wind energy system provides higher system performance than either of the single system, for the same system cost and battery storage capacity. It was also observed that the magnitude of the battery storage capacity has important bearing on the system performance of single PVs and wind energy system.

Chedid and Rahman [50] presented controller design that monitors the operation of the autonomous or grid connected system. The controller determines the energy available from each of the system components and environmental credit of the system. The model developed can give production cost, unmet and spilled energies, and battery charged and discharged losses.

Decision support model for hybrid PV/wind energy system was discussed by Chedid et al. [10] based on political, social, technical, and economical issues. The authors have

quantified various divergencies of opinions, practices, events that lead to confusion and uncertainty in planning hybrid PV/wind energy system using analytical hierarchical method. Finally, the authors used trade-off risk method for generating multiple plans and obtained its trade-off curves to segregate robust and inferior plans based on their frequent occurrence in conditional decision set. Risk analysis was also performed to assign alternative options in case risky feature occurs.

Hybrid PV/wind energy systems are also designed not only for meeting electricity requirements but also for meeting fresh water requirements through desalination [65]. Sontag and Lange [66] made an attempt towards improving the prospects for utilizing renewable energies in combination with energy supply system, for the power and heating requirements of a residential complex.

Above discussed studies reveals that hybrid PV/wind energy system are proving to be very promising worldwide. In view of system costs, contribution of PV is small as compared to the share of wind. It is observed that PV to wind power ratio in hybrid PV/wind energy system in order to have least cost is 70% [7].

5. Trends in hybrid renewable energy system modeling

The classification of published literature is presented herewith a view to highlight trends in HRES modeling (Tables 1 and 2). Literature review reveals that over the last decades, HRES applications are growing rapidly and HRES technology has proven its competitiveness for remote area applications. Table 2 represents studies reported on various aspects of HRES like design/economics, control, and utility interactive. It is observed that approximately 90% of studies reported are on design/economic aspects of HRES. However, fewer studies were reported on control of HRES. Utility interactive HRES has yet not gained the popularity.

It is expected that within the next few years HRES becomes competitive with utility grid power for wide spread distributed applications. Hence, there is a need to investigate potential and performance of PV and wind energy system to calculate level of penetration in existing networks of developed or developing countries in order to improve quality of power supply [67,68]. It is also observed that PV and wind electricity can be introduced into the network, either by a centralized or by a distributed system. In a distributed system, power is produced at or close to the point of use. Distributed energy systems avoid the

Table 1
Hybrid power system configuration by year of publication

Year of publication publications	Upto 1995	Beyond 1995	Number of
Hybrid PV energy systems	[21]	[3,12,13,15–20,23,67,85]	13
Hybrid wind energy systems	[30,42]	[20,26,29,37,39–41,43,44,86]	12
Hybrid PV/wind energy systems	[49,53,54,56,61,87]	[1,2,4,7,8,10,14,45–48,50,52,55,57–60,62–65,88]	30
Total	9	46	

Numbers in square brackets refer to reference numbers.

Table 2
Classification of studies reported on hybrid renewable energy systems

Year of publication	Design/economics	Control	Utility interactive	Number of publications
PV and hybrid PV energy systems	[3,12,13,15–21,23,85]		[67]	13
Wind and hybrid wind energy systems	[20,25–37,39–42,86]	[37,39]	[43,44]	23
Hybrid PV/wind energy systems				
[1,2,4,7,8,10,14,20,45,46,48–66,87]	[50,88]	[47]	33	
Total	61	04	04	

Numbers in square brackets refer to reference numbers.

costs and losses of transmission and distribution. Therefore, there is need to identify locations for installing PV and wind energy systems and their interconnections with the utility grid, in order to minimize the cost of electricity without disturbing the existing network.

Economic value of the power produced, given the plant location and its trend of power production is defined as power value of the system. Power value is affected by the distance between the power station and the load and by the match/mismatch conditions of the production with the trends of the load. The power value varies instant by instant depending on the present level of power production and surrounding load conditions. The power value of HRES in the grid takes into account the reduction of energy production costs (savings in fuel consumption, operation and maintenance cost, etc.), the transportation costs and, in some cases, the risk reduction as regards the possible situations of scarcity in given periods (peak hours). However, the power value of HRES may be increased by the following distributed benefits in terms of reduction of Joule losses, improvement in quality of service in peak hours (voltage stability, improvement in continuity of service in peak hours, deferral and/or reduction of investment to upgrade the power distribution network, reduction of additional generation capacity, and reduction of environmental impacts.

In order to increase share of renewable energy sources in power generation capacity of the country, there is need to integrate PV or wind in the conventional network system. The main obstacle to grid-connected PV or wind is presented by the limitations of the power distribution networks. Instantaneous power production from PV or wind often exceeds the instantaneous power consumption of the network, with a high concentration. In many cases, the imbalance in power creates a net power flow backwards through the medium/low-voltage transformers. However, this problem can be overcome by accurately predicting the levels of PV penetration in the network.

A classification of published literature before 1995 and beyond 1995 is also presented in Table 1. Reviewed literature reports studies on hybrid PV/wind energy system (56%), followed by Hybrid PV energy systems (23%), and Hybrid Wind energy system (21%). Other possible hybrid combinations inclusive of hydro [69], biomass [70–72], fuel cell [73–75], municipal waste [72,76], and combined heat and power [77,78] are still in development and research phase only. In the era of environment concern, reevaluation of HRES can be done from point of view of CO_2 taxation [79]. Technological advances include power quality monitoring and stability [80,81]; reliability evaluation [82], decision

support technique [10,83], and advances in control technology [38,39,51,84] have to be considered for future design and modeling.

7. Conclusions

Published literature on hybrid renewable energy systems (HRES) modeling indicates its popularity in terms of meeting specific energy demands. HRESs are mainly recognized for remote area power applications and are now a days cost-effective where extension of grid supply is expensive. Although, the cost and technological development of HRES in recent years has been encouraging, they remain an expensive source of power. HRES provides prospects of incorporating in power generation capacity to improve power quality, due to the dispersed generation. This integration results in increasing power value of conventional generation and also provides market for penetration of renewable energy systems. In order to introduce HRES in existing power supply network, in depth study is to be carried out to check feasibility and technical competitiveness. Penetration levels on network basis, is the future of hybrid power system in power generation capacity of the country, as outlined in this paper. Paper also, present future development, which will allow a further expansion of markets, both in developed and developing countries.

Acknowledgments

The authors acknowledge for the constructive suggestions, criticism and support of Dr. S.D. Pohekar, BITS, Pilani.

References

[1] Elhadidy MA, Shaahid SM. Parametric study of hybrid (wind + solar + diesel) power generating systems. Renew Energy 2000;21(2):129–39.
[2] Elhadidy MA, Shaahid SM. Promoting applications of hybrid (wind + photovoltaic + diesel + battery) power systems in hot regions. Renew Energy 2004;29(4):517–28.
[3] Notton G, Muselli M, Louche A. Autonomous hybrid photovoltaic power plant using a back-up generator: a case study in a Mediterranean Island. Renew Energy 1996;7(4):371–91.
[4] Karaki SH, Chedid RB, Ramadan R. Probabilistic performance assessment of autonomous solar–wind energy conversion systems. IEEE Trans Energy Convers 1999;14(3):766–72.
[5] Duffie JA, Beckman WA. Solar engineering of thermal processes, 2nd ed. USA: Wiley; 1991.
[6] Markvart T. Solar electricity, 2nd ed. USA: Wiley; 2000.
[7] Habib MA, Said SAM, El-Hadidy MA, Al-Zaharna I. Optimization procedure of a hybrid photovoltaic wind energy system. Energy 1999;24:919–29.
[8] Kolhe M, Agbossou K, Hamelin J, Bose TK. Analytical model for predicting the performance of photovoltaic array coupled with a wind turbine in a stand-alone renewable energy system based on hydrogen. Renew Energy 2003;28(5):727–42.
[9] Patel MR. Wind and solar power systems. UK: CRC Press; 1999.
[10] Chedid R, Akiki H, Rahman S. A decision support technique for the design of hybrid solar–wind power systems. IEEE Trans Energy Convers 1998;13(1):76–83.
[11] Nag PK. Power plant engineering, 2nd ed. New Delhi: Tata McGraw-Hill Publishers Co. Ltd.; 2001.
[12] El-Hefnawi SH. Photovoltaic diesel–generator hybrid power system sizing. Renew Energy 1998;13(1):33–40.
[13] Bhuiyan MMH, Asgar MA. Sizing of a stand-alone photovoltaic power system at Dhaka. Renew Energy 2003;28(6):929–38.
[14] Ai B, Yang H, Shen H, Liao X. Computer-aided design of PV/wind hybrid system. Renew Energy 2003;28(10):1491–512.

[15] Shaahid SM, Elhadidy MA. Opportunities for utilization of stand-alone hybrid (photovoltaic + diesel + battery) power systems in hot climates. Renew Energy 2003;28(11):1741–53.
[16] Shaahid SM, Elhadidy MA. Prospects of autonomous/stand-alone hybrid (photo-voltaic + diesel + battery) power systems in commercial applications in hot regions. Renew Energy 2004;29(2):165–77.
[17] Valente LCG, Almeida SCAD. Economic analysis of a diesel/photovoltaic hybrid system for decentralized power generation in northern Brazil. Energy 1998;23(4):317–23 [Hard + SOFT COPY].
[18] Muselli M, Notton G, Poggi P, Louche A. PV–hybrid power systems sizing incorporating battery storage: an analysis via simulation calculations. Renew Energy 2000;20(1):1–7.
[19] Shrestha GB, Goel L. A study on optimal sizing of stand-alone photovoltaic stations. IEEE Trans Energy Convers 1998;13(4):373–8.
[20] Kellogg WD, Nehrir MH, Venkataramanan G, Gerez V. Generation unit sizing and cost analysis for stand-alone wind photovoltaic and hybrid wind/PV systems. IEEE Trans Energy Convers 1998;13(1): 70–5.
[21] Abouzahr I, Ramakumar R. Loss of power supply probability of stand-alone photovoltaic systems: a closed form solution approach. IEEE Trans Energy Convers 1991;6(1):1–11.
[22] Egido M, Lorenzo E. The sizing of stand alone PV-systems: a review and a proposed new method. Solar Energy Mater Solar Cells 1992;26:51–69.
[23] Marwali MKC, Shahidehpour SM, Daneshdoost M. Probabilistic production costing for photovoltaic-utility systems with battery storage. IEEE Trans Energy Convers 1997;12(2):175–80.
[24] Wichert B. PV–diesel hybrid energy systems for remote area power generation—a review of current practices and future developments. Renew Sustain Energy Rev 1997;1(3):209–28.
[25] Mathew S, Pandey KP, Anil Kumar V. Analysis of wind regimes for energy estimation. Renew Energy 2002;25(3):381–99.
[26] Elhadidy MA, Shaahid SM. Role of hybrid (wind + diesel) power systems in meeting commercial loads. Renew Energy 2004;29(1):109–18.
[27] Papadopoulos DP, Dermentzoglou JC. Economic viability analysis of planned WEC system installations for electrical power production. Renew Energy 2002;25(2):199–217.
[28] Rehman S, Halawani TO, Mohandes M. Wind power cost assessment at twenty locations in the kingdom of Saudi Arabia. Renew Energy 2003;28(4):573–83.
[29] Nfaoui H, Buret J, Sayigh AAM. Cost of electricity generated and fuel saving of an optimized wind-diesel electricity supply for village in Tangier-area Morocco. Renewable Energy: World Renewable Energy Congress, June 1996 at Colorado USA, 1996, p. 831–5.
[30] Nfaoui H, Buret J, Sayigh AMM, Dunn PD. Modeling of a wind/diesel system with battery storage for Tangier Morocco. Renew Energy 1994;4(2):155–67.
[31] Li S, Wunsch DC, O'Hair E, Giesselmann MG. Comparative analysis of regression and artificial neural network models for wind turbine power curve estimation. J Solar Energy Eng 2001;123:327–32.
[32] Kariniotakis GN, Stavrakakis GS, Nogaret EF. Wind power forecasting using advanced neural networks models. IEEE Trans Energy Convers 1996;11(4):762–7.
[33] Feijoo AE, Cidras J, Dornelas JLG. Wind speed simulation in wind farms for steady-state security assessment of electrical power systems. IEEE Trans Energy Convers 1999;14(4):1582–8.
[34] Salameh ZM, Safari I. The effect of the windmill's parameters on the capacity factor. IEEE Trans Energy Convers 1995;10(4):747–51.
[35] Roy S. Optimal planning of wind energy conversion systems over an energy scenario. IEEE Trans Energy Convers 1996;12(3):248–54.
[36] Jangamshetti SH, Guruprasada RV. Optimum sitting of wind turbine generators. IEEE Trans Energy Convers 2001;16(1):8–13.
[37] Delarue P, Bouscayrol A, Tounzi A, Guillaud X, Lancigu G. Modeling, control and simulation of an overall wind energy conversion system. Renew Energy 2003;28(8):1169–85.
[38] Bhatti TS, Al-ademi AAF, Bansal NK. Load–frequency control of isolated wind–diesel–microhydro hybrid power systems. Energy 1997;22(5):461–70.
[39] Chedid RB, Karaki SH, El-Chamali C. Adaptive fuzzy control for wind–diesel weak power system. IEEE Trans Energy Convers 2000;15(1):71–8.
[40] Celik AN. A simplified model for estimating the monthly performance of autonomous wind energy systems with battery storage. Renew Energy 2003;28(4):561–72.
[41] Elhadidy MA, Shaahid SM. Optimal sizing of battery storage for hybrid (wind + diesel) power systems. Renew Energy 1999;18(1):77–86.

[42] Abouzahr I, Ramakumar R. Loss of power supply probability of stand-alone wind electric conversion systems: a closed form solution approach. IEEE Trans Energy Convers 1990;5(3):445–52.
[43] Mohammed H, Nwankpa CO. Stochastic analysis and simulation of grid-connected wind energy conversion system. IEEE Trans Energy Convers 2000;15(1):85–90.
[44] Karki R, Billinton R. Cost-effective wind energy utilization for reliable power supply. IEEE Trans Energy Convers 2004;19(2):435–40.
[45] Elhadidy MA. Performance evaluation of hybrid (wind/solar/diesel) power systems. Renew Energy 2002; 26(3):401–13.
[46] Bhave AG. Hybrid solar–wind domestic power generating system—a case study. Renew Energy 1999;17(3): 355–8.
[47] Giraud F, Salameh ZM. Steady-state performance of a grid-connected rooftop hybrid wind–photovoltaic power system with battery storage. IEEE Trans Energy Convers 2001;16(1):1–7.
[48] McGowan JG, Manwell JF, Avelar C, Warner CL. Hybrid wind/PV/diesel hybrid power systems modeling and South American applications. Renewable Energy: World Renewable Energy Congress, June 1996 at Colorado USA, 1996, p. 836–47.
[49] Gomaa S, Seoud AKA, Kheiralla HN. Design and analysis of photovoltaic and wind energy hybrid systems in Alexandria, Egypt. Renew Energy 1995;6(5–6):643–7.
[50] Chedid R, Rahman S. Unit sizing and control of hybrid wind–solar power systems. IEEE Trans Energy Convers 1997;12(1):79–85.
[51] Chedid R, Saliba Y. Optimization and control of autonomous renewable energy systems. Int J Energy Res 1996;20:609–24.
[52] Bagul AD, Salameh ZM, Borowy B. Sizing of stand-alone hybrid wind–photovoltaic system using a three-event probability density approximation. Solar Energy 1996;56(4):323–35.
[53] Musgrove ARD. The optimization of hybrid energy conversion system using the dynamic programming model—RAPSODY. Int J Energy Res 1988;12:447–57.
[54] Yokoyama R, Ito K, Yuasa Y. Multi-objective optimal unit sizing of hybrid power generation systems utilizing photovoltaic and wind energy. J Solar Energy Eng 1994;116:167–73.
[55] Karki R, Billinton R. Reliability/cost implications of PV and wind energy utilization in small isolated power systems. IEEE Trans Energy Convers 2001;16(4):368–73.
[56] Samarakou MT, Grigoriadou M, Caroubalos C. Comparison results of two optimization techniques for a combined wind and solar power plant. Int J Energy Res 1988;12:293–7.
[57] Al-Ashwal AM, Moghram IS. Proportion assessment of combined PV–wind generating systems. Renew Energy 1997;10(1):43–51.
[58] Yang HX, Lu L, Burnett J. Weather data and probability analysis of hybrid photovoltaic–wind power generation systems in Hong Kong. Renew Energy 2003;28(11):1813–24.
[59] Beyer HG, Langer C. A method for the identification of configurations of PV/wind hybrid systems for the reliable supply of small loads. Solar Energy 1996;57(5):381–91.
[60] Protogeropoulos C, Brinkworth BJ, Marshall RH. Sizing and techno-economical optimization for hybrid solar photovoltaic/wind power systems with battery storage. Int J Energy Res 1997;21:465–79.
[61] Hennet JC, Samarakou MT. Optimization of a combined wind and solar power plant. Energy Res 1986;10:181–8.
[62] Celik AN. Optimization and techno-economic analysis of autonomous photovoltaic–wind hybrid energy systems in comparison to single photovoltaic and wind systems. Energy Convers Manage 2002; 43(18):2453–68.
[63] Nehrir MH, LaMeres BJ, Venkataramanan G, Gerez V, Alvarado LA. An approach to evaluate the general performance of stand-alone wind/photovoltaic generating systems. IEEE Trans Energy Convers 2000;15(4): 433–9.
[64] Celik AN. The system performance of autonomous photovoltaic–wind hybrid energy systems using synthetically generated weather data. Renew Energy 2002;27(1):107–21.
[65] Manolakos D, Papadakis G, Papantonis D, Kyritsis S. A simulation-optimization programme for designing hybrid energy systems for supplying electricity and fresh water through desalination to remote areas case study: the Merssini village, Donoussa Island, Aegean Sea, Greece. Energy 2001;26(7):679–704.
[66] Sontag R, Lange A. Cost effectiveness of decentralized energy supply systems taking solar and wind utilization plants into account. Renew Energy 2003;28(12):1865–80.
[67] Abdullah AH, Ghoneim AA, Al-Hasan AY. Assessment of grid-connected photovoltaic systems in the Kuwaiti climate. Renew Energy 2002;26(2):189–99.

[68] Kabouris J, Contaxis GC. Autonomous system expansion planning considering renewable energy sources—a computer package. IEEE Trans Energy Convers 1992;7(3):374–81.
[69] Bakos GC. Feasibility study of a hybrid wind/hydro power—system for low-cost electricity production. Appl Energy 2002;72:599–608.
[70] Jurado F, Saenz JR. Neuro-fuzzy control for autonomous wind–diesel systems using biomass. Renew Energy 2002;27(1):39–56.
[71] Jurado F, Saenz JR. Possibilities for biomass-based power plant and wind system integration. Energy 2002;27(10):955–66.
[72] McGowin CR, Wiltsee GA. Strategic analysis of biomass and waste fuels for electric power generation. Biomass Bioenergy 1996;10(2–3):167–75.
[73] Iqbal MT. Modeling and control of a wind fuel cell hybrid energy system. Renew Energy 2003;28(2):223–37.
[74] Iqbal MT. Simulation of a small wind fuel cell hybrid energy system. Renew Energy 2003;28(4):511–22.
[75] El-Shatter TF, Eskandar MN, El-Hagry MT. Hybrid PV/fuel cell system design and simulation. Renew Energy 2002;27(3):479–85.
[76] Murphy JD, McKeogh E. Technical, economic and environmental analysis of energy production from municipal solid waste. Renew Energy 2004;29(7):1043–57.
[77] Lund H, Munster E. Modeling of energy systems with a high percentage of CHP and wind power. Renew Energy 2003;28(14):2179–93.
[78] Lund H, Ostergaard PA. Electric grid and heat planning scenarios with centralized and distributed sources of conventional CHP and wind generation. Energy 2000;25:299–312.
[79] Santisirisomboon J, Limmeechokchai B, Chungpaibulpatana S. Impacts of biomass power generation and CO_2 taxation on electricity generation expansion planning and environmental emissions. Energy Policy 2001; 29(12):975–85.
[80] Oliva AR, Balda JC, McNabb DW, Richardson RD. Power-quality monitoring of a PV generator. IEEE Trans Energy Convers 1998;13(2):188–93.
[81] Ro K, Rahman S. Control of grid-connected fuel cell plants for enhancement of power system stability. Renew Energy 2003;28(3):397–407.
[82] Gautam NK, Kaushika ND. Reliability evaluation of solar photovoltaic arrays. Solar Energy 2002;72(2): 129–41.
[83] Mamlook R, Akash BA, Mohsen MS. A neuro-fuzzy program approach for evaluating electric power generation systems. Energy 2001;26:619–32.
[84] Jurado F, Saenz JR. An adaptive control scheme for biomass-based diesel–wind system. Renew Energy 2003;28(1):45–57.
[85] Linde HAV, Sayigh AAM. The economics of a solar/diesel hybrid—a case study. Renewable Energy: World Renewable Energy Congress, June 1996 at Colorado USA, 1996, p. 884–6.
[86] Karaki SH, Chedid RB, Ramadan R. Probabilistic production costing of diesel–wind energy conversion systems. IEEE Trans Energy Convers 2000;15(3):284–9.
[87] Gavanidou ES, Bakirtzis AG. Design of stand-alone system with renewable energy sources using trade off methods. IEEE Trans Energy Convers 1992;7(1):42–8.
[88] Valenciaga F, Puleston PF, Battaiotto PE. Power control of solar/wind generation system without wind measurement: a passive/sliding mode approach. IEEE Trans Energy Convers 2003;18(4):501–7.